60 years of the creation of the transistor.

Start of semiconductor applications

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This article reviews historical events associated with the first applications of semiconductor devices in radio devices.

Tube enslavement

In the years preceding World War II, during the war (1939-1945) and after it, radar and computer facilities developed rapidly. The enormous devices personifying the latter contained thousands of radio tubes, were energy-intensive, and occupied several rooms. For example, for the first time a functioning ENIAC computer (electronic numerical integrator and computer), shown in the USA on February 14, 1946, by a military and scientist, weighed 27 tons, contained 17,468 radio tubes and 7200 semiconductor diodes, consumed 150 kW of power and occupied 167 m2 area (Fig. 1). Computer scientists from around the world unofficially mark February 14th as "Computer Day." At the dawn of computing, the BESM computer created in the Soviet Union was not only inferior to its American counterparts, but was better than them. The tradition was continued in the 80s by the Elbrus computer. Nowadays, tube mastodons of the past surpasses the silicon "microchip" with an area of only 0.5 mm2 in "mental" abilities.

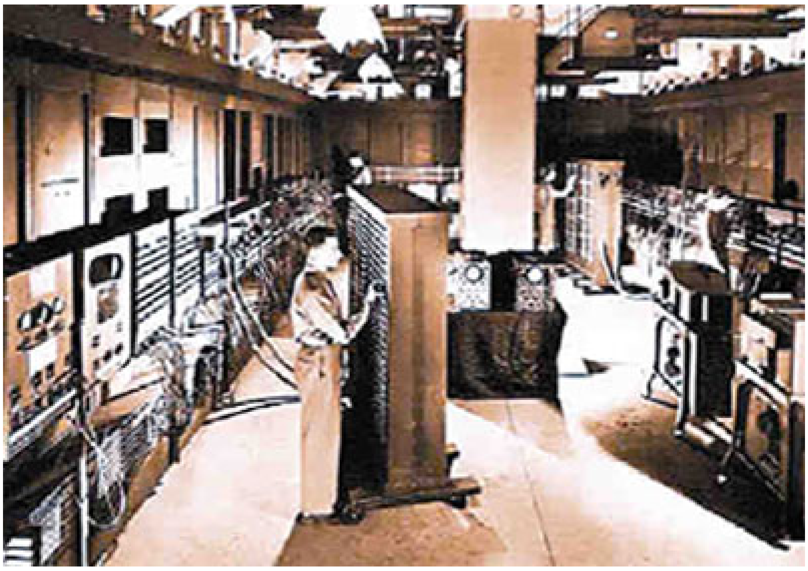

Fig. 1. Computer ENIAC

60 years ago

In the mid-1930s, due to the lack of an alternative to lamps, the imminent threat of gigantomania was fully recognized in the American (USA) research and development corporation BELL LABORATORIES (BL). Immediately after its establishment in 1925 [1], acoustic measurements in the organization began to be supervised by H. Fletcher (1884-1981), who by then became famous in physical research, co-founder (in 1929) and the first president of the Acoustic Society of America.

Prior to joining BL, H. Fletcher helped R. Milliken (1866-1953) conduct experiments to determine the elementary electric charge, which allowed him to receive the Nobel Prize in physics in 1923. In 1935, H. Fletcher was entrusted with leading all physical studies in Science Center BL. By the way, a little later, in 1949, he was elected president of the American Physical Society. H. Fletcher is known to Russian professionals and amateur radio enthusiasts for his widely used acoustics (since 1933) “equal-volume Fletcher-Manson curves”.

Theoretical physicist William Shockley (1910-1989), who was well acquainted with the theory and practice of setting up laboratory experiments, was invited to work at BL New York Center in 1936. At that time, work that developed telephone communications with fewer relays and electronic tubes was considered paramount. . By 1939, Shockley put forward the conceptual idea of switching telephony from electrovacuum devices and electromechanical switches to solid-state amplifiers. He suggested that if a semiconductor is able to detect an alternating electric signal, then it is quite possible that there is a mechanism for its amplification under the influence of an electric field. It should be recalled that in solid state physics the theory of donor (electron) and acceptor (hole) semiconductivity was developed in 1930-1931. However, the trial work implementing the idea was not successful then. The ongoing experiments were prevented by the outbreak of World War II.

A return to the experiments was obtained in 1945 already in the new territory allocated by BL in the Murray Hill region of New Jersey. The Shockley-led group included Walter Brattain (1902-1987), a physicist and researcher who worked at BL since 1929, and theoretical physicist John Bardin (1908-1991), a fellow student at Shockley University. In addition to them, the team included a physicist-chemist, three experimental engineers, among whom was an electronics engineer, and five assistants.

Shockley and Bardin had the impression that germanium could serve as the main material for a device that could replace a vacuum triode. In the periodic table compiled by D. I. Mendeleev (1834-1907) in 1869, there was initially no germanium, but its existence was predicted. The discovery of the material took place in 1885. Semiconductor (PP) properties in Germany were discovered in 1929.

At the end of 1946, Bardin proposed checking the hypothesis put forward in 1943 by student R. Bray (1921-2006) from Purdue University (Indiana) that electrons in a semiconductor are grouped closer to its surface. To improve the interaction with an external electric field, the surfaces of germanium crystals began to be polished or, on the contrary, matted, treated with passivating solutions, moistened with active liquids, as well as ordinary and distilled water, etc. Obviously, in addition to the theoretical provisions for revealing the secrets of the PP effect, they also moved forward and through trial and error or, speaking scientifically, by the method of successive approximations.

The work reached a high level in the last months of 1947. In the laboratory, Brattain spent the most time. He belongs to the idea of making the electrodes “antennae” in contact with the crystal surface with hairs (the thickness of a human hair) and placing them closer to each other. Once, when changing the polarity of the supplied voltages, he was lucky to see the amplified signal on the oscilloscope screen.

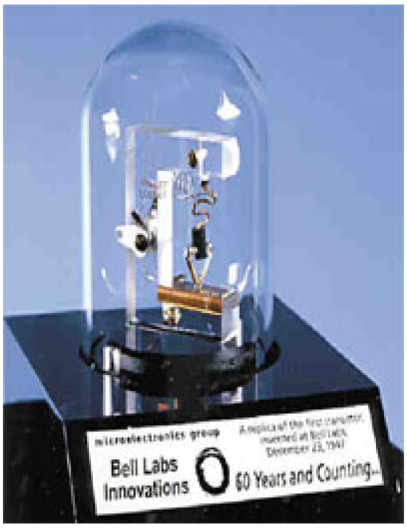

Fig. 2. Contact point device

The event took place on Monday, December 15, 1947. In a laboratory journal, Bratstein wrote: “When contact points came closer together, the voltage achieved was 2 V in the frequency band from 10 to 10,000 cycles” [2]. The next day, December 16, he stated there: “The distance between the points of the electrodes was 4 × 10-3 cm.” On the same day, the PP phenomenon was demonstrated to the group. Bardin was able to quickly develop a theoretical model of the discovery. However, the postulate of his theory about the transfer of not electrons in a crystal, but “holes” from the emitter to the collector, was not accepted by many physicists until the end of the 1950s.

In the middle of the day, December 23, the contact point device (Fig. 2) was presented to the Deputy Director of BL for Science, R. Bone (1891-1971), H. Fletcher, as well as to the leading engineering and technical workers of some related organizations and authorized from the military department. The inventors explained that the term transistor (transistor), coined by him, was obtained from a combination of the parts of two words transfer or transconductance (transient conductivity) and varistor (non-linear resistor). Those present did not find the point contacts in the crystal reliable and therefore found it difficult to recommend its use. The military did not like the dependence of the characteristics of the transistor on changes in ambient temperature. A wish was expressed to try to innovate in hearing aids.

Fig. 3. Bardin, Brattain and Shockley

Bone made a public appearance before reporters and a few representatives to the academic community six months later, on Wednesday, June 30, 1948, in the conference hall of the BL New York branch. The significance of the invention of PP amplifier triode was not understood. The statement about the modest dimensions of the transistor and its low power consumption did not make a special impression on the public. Some newspapers limited themselves to brief reports about the presentation and the element shown there - a "wick" the size of half an inch (12.7 mm).

Shockley understood the importance of the work done, but he considered it incomplete. In the next short period of time, he developed the theoretical justification and design of a planar transistor, put into practice in July 1951. The three main participants in the intense and creative work on creating a transistor - Bardin, Brattein and Shockley (Fig. 3) in 1956 were awarded the Nobel premiums. At the award ceremony, they came together for the last time. Then the scientists no longer met, because they worked in different companies.

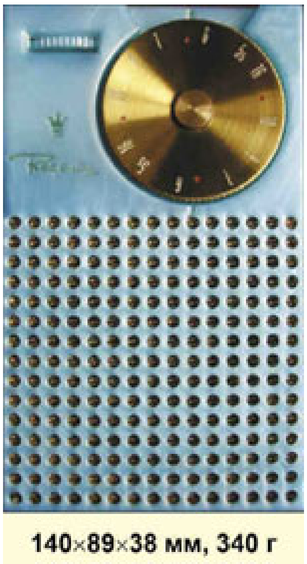

Fig. 4. TR-1

In the late 1950s, the band theory of the conductivity of semiconductors in Europe was not yet adopted. Americans who spoke at academic sessions and symposia sometimes resorted to imaginative explanations and visual aids. At the 1960 International Conference on Semiconductor Physics in Budapest, for example, at the end of the talk, Shockley turned his back to the hall and lifted the bottom of his jacket. Listeners saw a rag hanging from the belt in the middle of the back, dividing half of the soft spot. Clapping a rag, he would say: "This is what pn transition is!" [3].

It should be noted that in 1972, Bardin received another Nobel Prize for his work in the field of superconductivity (the only case in the history of awards!). The scientific interests and the second half of the life of the authors of the epoch-making invention can be found in more detail in [4].

The importance and significance of PP topics was understood by the US government. In the 1950s, enterprises introducing the development of new technology received tax benefits. In 1952, the in-line production of the famous transistor SK722 mastered the well-known and large military enterprise RAYTHEON in Massachusetts. At the beginning of next year, the company's manufactured transistors became available to the consumer market. They were recommended for use in portable radios, electrical meters, timers for photo printing and hearing aids. In the spring of the same year, the Acoustion hearing aid appeared on a single transistor with a large gain, and a little later, a "louder" device with an RF amplifier on three transistors. In 1953, in total about 1 million transistors were produced in the USA, in 1955 - 3.5 million, in 1957 - 29 million.

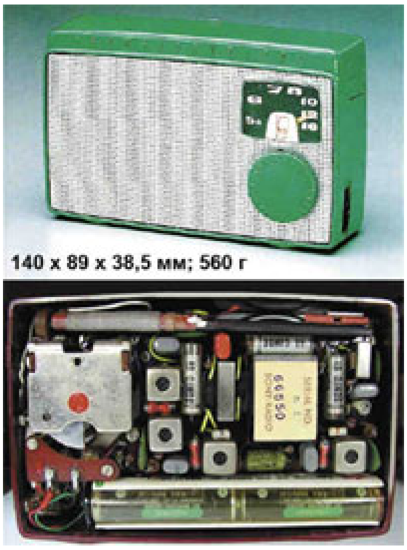

Fig. 5. TR-55

The first medium-wave (640 ... 1240 kHz) superheterodyne pocket radio receiver with four transistors was produced by REGENCY DIVISION of IDEA in Indianapolis. It received the name TR-1 (Fig. 4), made on a printed circuit board. The TR-1 was introduced to the general public in early 1954. Six months later, it went on sale. It was mass-produced for five years.

In 1953, a little-known then Japanese company with the sonorous name SONY bought a license to manufacture transistors from BL. Since August 1955, she began distributing her first transistors (five) of medium-wave superheterodyne receivers TR-55 (Fig. 5). In 1965, SONY reported on the release of 40,000 portable receivers of the upgraded TR-72 model. The receivers went for export to North America and Europe. A competing product that appeared to Americans (mostly young) preferred the more sensitive and loud sound.

The advent of the transistor in Russia

In our country, a germanium transistor was reproduced in 1949 in a laboratory led by A. V. Krasilov and belonging to the PULSAR Scientific Research Institute in the city of Fryazino near Moscow [5]. The first planar alloy transistors were also manufactured there. The laboratory studied the characteristics of semiconductors, developed prototypes of amplifiers, radios, transistors based on transistors, suitable for the civilian and military spheres.

The circuit of a miniature radio receiver with direct amplification on a single transistor was presented in the magazine “Radio” in 1956 in materials from the German Hanover exhibition. After that, a number of other articles on PP devices appeared in the magazine. In 1958, a diagram and description of the design of the receiver of V. Plotnikov, which received popularly (amateur) recognition, was published [6].

From the history of semiconductors

In 1826, the German physicist G. Om (1787-1854) formulated the famous, bearing his name, law on the direct proportional dependence of the current in the circuit on the applied emf. In 1833, the outstanding English self-taught physicist M. Faraday (1791-1867) found that the resistance of silver sulfide (a compound with a gray metal) does not differ in constancy in the electric circuit. It decreases with heating of the material, and the current increases [4, 7].

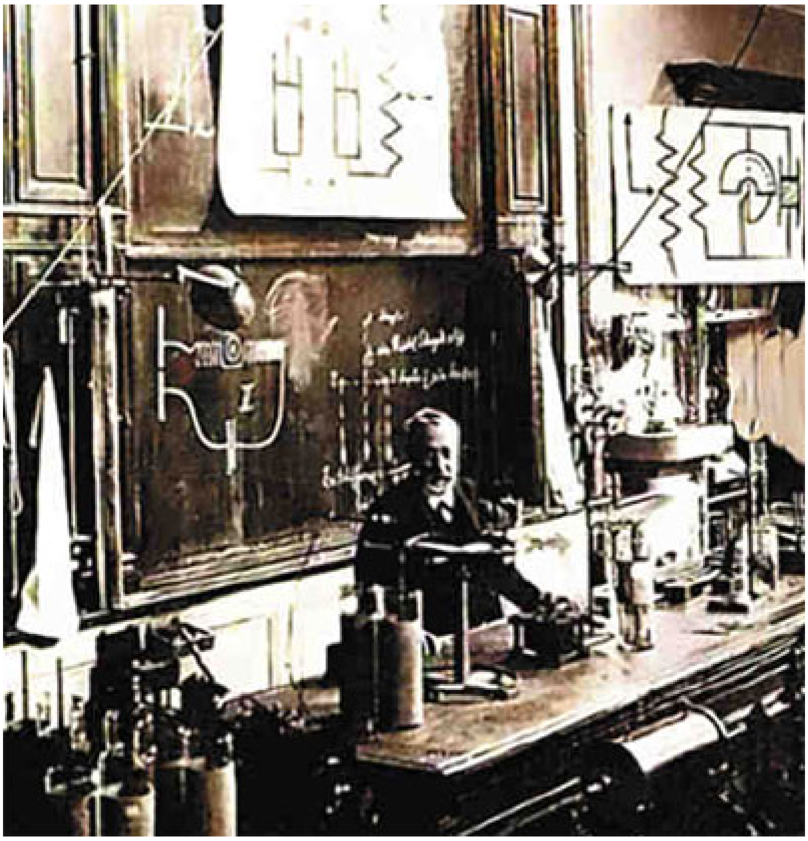

Fig. 6. K. F. Brown

In 1874, another German physicist K.F. Brown (1850-1918), as a young teacher of natural sciences in high school (Fig. 6), in his spare time studied materials whose behavior in the electric circuit also did not meet Ohm's law. He discovered a number of crystals with one-sided conductivity. The established effect was even more noticeable upon the contact of heterogeneous crystals or a crystal with a metal. Brown described the results of his research in four published articles, the first of which he published at the end of 1874.

Brown's experiments were repeated by the famous non-German physicist-electrician V.E. Siemens (1816-1892) and confirmed his conclusions. In 1899, Brown studied the possibility of replacing the coherer used by the receivers of A.S. Popov (1859-1906) and G. Marconi (1874-1937) with one of the semiconductors tested by him. However, he did not receive a persistent improvement in the result of receiving pulsed telegraph signals and refused further tests [8].

It is appropriate to report that Brown in the late nineteenth and early twentieth centuries introduced a number of improvements to wireless telegraph devices, and founded his own wireless communications company (1898). In addition, he proposed a model of a cathode oscillographic tube (1897) for controlling fast processes. In 1909, according to the results of the work performed, together with Marconi Brown, he was awarded the Nobel Prize in physics. A. S. Popov personally met with Brown and was in correspondence with him. The German physicist highly appreciated the devices created by the Russian scientist, admitted that the Marconi devices identical to them were made later [9].

Semiconductor start of the radio

Researchers and inventors began to study powders and mixtures of materials that change resistance under the influence of stress on them back in the middle of the XVIII century [10]. In 1833, the Swedish physicist M.S. Munk (1804-1860) constructed a glass tube with two leads, into which powders of coal, tin, and mercury sulfide were placed. Munk discharged the charged Leiden jar through this tube onto his own body and so physiologically "on himself" checked the electrical conductivity of the powders. Munch determined that after shaking, the resistance of the powder in the flask was restored. In 1866, a tube filled with coal powder mixed with an insulating substance was used by the Varley brothers in England for lightning protection of telegraph lines.

Beginning in 1890, the French physicist E. Branly (1844-1940) began experimenting with ebonite and glass tubes, filling them with sawdust of copper, iron, zinc, aluminum, and others. On slightly elongated leads of wires from the tube and a sensitive arrow connected in series with it Branly's indicator received spark discharges from an electrification machine or self-induction emitting coil of a German G. Rumkorf's coil (1803–1877). In 1894, the English physicist O. Lodge (1851-1940) called the "Branly Tube" a coherer (from Latin cohaerere - to interlock). The scientists discovered the mechanism of adhesion of sawdust, improve their electrical conductivity under the influence of electromagnetic waves (EMC) has not found a satisfactory explanation so far.

In a radio receiver invented at the end of the 19th century, the coherer detected weak pulse-modulated RF signals. There was no alternative to him. European and American scientists and engineers related to wireless telegraphy were forced to put up with the coherer's shortcomings (the need to "shake" it after passing every impulse). At that time, none of the "bright minds" of physics and electrical engineering had the idea to offer something better.

A. S. Popov - thrice inventor of radio

The discovery made on May 20, 1899 (a historic day!) By Popov's assistants, P. N. Rybkin (1864-1948) and D. S. Troitsky (1857-1918), helped. They were the first to hear telegraph parcels coming over the air. Popov took the possibility of receiving "by ear" modulated EMC very seriously. He understood the prospects opening up to radio equipment. The circuitry developed on the basis of the discovery of a new "receiver of desks" designed by him was simplified, sensitivity increased at the same time, dimensions and weight were reduced, and energy consumption decreased [11].

Sound reproduction in the receiving equipment was Popov's second contribution to the invention of radio. However, the coherer detecting the input signals remained. Although the "shake" it was no longer necessary. However, the internal "sand" filling of the tube, requiring a careful attitude to the device, did not contribute to its high reliability. Popov did not satisfy such a detector.

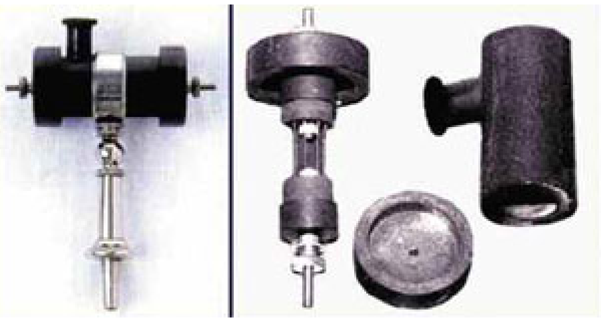

Fig. 7. Detector developed by Popov in 1900

It was decided to independently carry out laboratory work on the selection of materials into semiconductor pairs, replacing the coherer and also providing the selection of signals without a significant drop in their level. By studying the physical properties of substances and experimenting, it was found that the greatest ability to detect are individual crystals in combination with metals. Structurally, the combination of ingredients took the form of a contact-point pair in the form of a pointed metal needle in contact with a small part of the surface of the crystal.

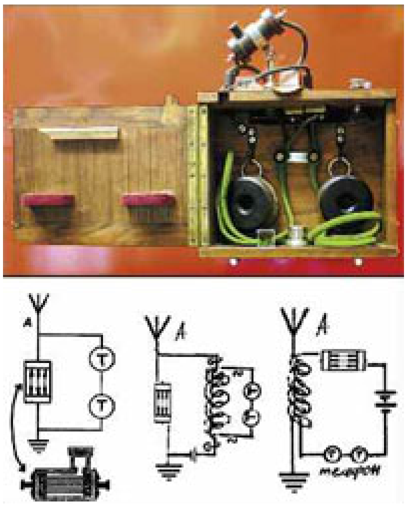

Fig. 8. Telephone receiver dispatch

The detector developed in 1900 by Popov is shown in Fig. 7 (from the funds of the Central Museum of Communications named after A. S. Popov). It is an ebonite cylinder with steel needles inside, abutting on screw-on carbon washers, covering the holes of the tube. A perpendicular, also cylindrical, protrusion on its body serves to drain the condensate that precipitates when the temperature decreases. In fig. 8 (also from the museum named after A. S. Popov) the detector "telephone receiver despatch" designed by the inventor and three variants of its outline schemes are depicted. Receivers with a coherer and a crystal detector with headphone access were patented by Popov in Russia and several European countries [11]. The introduction of a semiconductor point-to-point diode into the airborne reception equipment was Popov's third major contribution to the invention of radio.

It was also obvious to Popov that the new receivers would be able to reproduce speech as well. And so in 1903, along with S. Ya. Livshits, who came to Moscow from graduate students to him on the basis of the created receiving and transmitting system, he conducted test broadcasts of voice messages [12]. In a radiotelephone station, the RF signal of the spark generator was modulated by the RF component of the microphone.

In January 1904, wireless speech transmission over a distance of 2 km was demonstrated at the Third All-Russian Electrotechnical Congress. It can be pointed out that MARCONI COMPANY recognized the need for amplitude-modulated speech and music transmissions by EMC only in 1915, and started developing on the basis of lamp technology.

Followers of Popov

The successful work of the Russian scientist encouraged engineers in other countries involved in wireless telegraphy and telephony to implement their own ideas for creating detectors different from the coherer. The first to respond was Marconi. In 1902, his company proposed a rather complex "string" magnetic detector, which functions thanks to a wire drawn, as in a tape recorder, between the poles of two magnets at a speed of 12.1 cm / s. The energetic entrepreneur managed to place several of these detectors on Italian sea vessels and on the infamous British liner Titanic. Due to its large size and mass, a device that is unique in its curiosity is not widespread.

A little more about the connection with the collapse of the Titanic. On the afternoon of April 14, 1912, the receiving radio equipment on the Titanic failed. A few hours before the collision with the iceberg (at 23 h 40 min), technical troubles in the ship's radio room were eliminated. In the process of receiving and transmitting telegrams to assist passengers, the electromechanical detector worked fine. But the vanity of Marconi prevented. Since 1904, Marconi has insisted on introducing into the international practice his developed CQD distress signal. In 1906, the Maritime Conference in Berlin (Germany) proposed a simpler and more understandable SOS signal for marine radio operators (and not only them). However, on all boats equipped with MARCONY COMPANY transmitting and receiving equipment, radio operators were obliged to focus on CQD.

When the Titanic began to sink, the CQD signal was broadcast. The ships in the Atlantic Ocean did not understand its main meaning. They received an explanation from a radio station located on the American coast [13]. Then, with delay, the Karpatia liner closest to the Titanic (93 km) turned to the crash site. Less than half (705) of people who got off or jumped overboard were saved. Half an hour after the start of the transmission of alarm signals, SOS and CQD signals began to be transmitted alternately. In June 1912, Marconi had to make excuses to the investigation for unsatisfactory distress signals. Marconi no longer claimed authorship in signaling at sea.

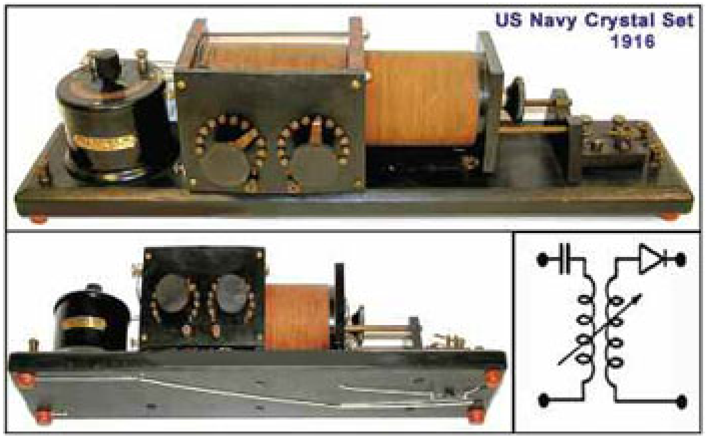

Fig. 9. Army radio sample 1916

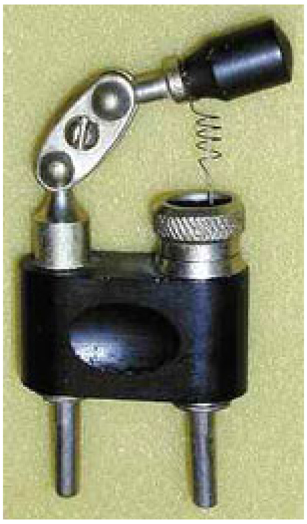

Fig. 10. Contact Point Crystal Detector

In early 1903, an American engineer R. Fessenden (1866-1932) invented an electrolytic detector [11]. Some historians of science believe that another American engineer-physicist of Serbian origin M. Pupin (1858-1935) paved the way for him, who began to study a liquid detector in 1899. Electrolytic detectors similar to the principle of their action, as well as a thermodetector, were developed in German research centers . For several years, liquid detectors were used in radio communications, but then, due to their low reliability, they were no longer used.

In 1906, an American engineer G. Picard (1877-1956) and General G. Danwoody (1842-1933) proposed installing crystal detectors based on silicon and carborundum in the receiving equipment, respectively. In subsequent years, in all developments of serial radio equipment, contact point diodes were preferred. Interesting descriptions of various rectifier devices developed for communication technology at the beginning of the last century can be found in [14]. The appearance and diagram of the American (USA) army radio receiver of the 1916 model with a Danwoody detector can be seen in Fig. 9 (from the funds of the E. T. Krenkel Museum of Radio and Amateur Radio).

By the beginning of the 1920s, a contact point crystalline detector acquired the configuration of a unified plug insert (Fig. 10) and in this form received widespread acceptance among serial equipment manufacturers and amateur radio enthusiasts. With such an insert or a similar one, the P-2 detector receiver (Fig. 11) and other models were mass-produced in Russia.

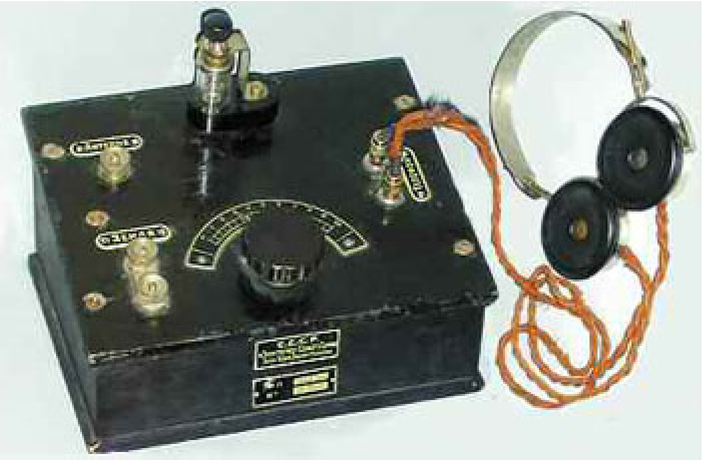

Fig. 11. Detector receiver P-2

In 1924, the magazine "Amateur Radio" came up with an interesting diagram of a home-made detector receiver without a variable capacitor, gave a description of its design. Thousands of enthusiasts in circles and at home repeated the model adapted in the Nizhny Novgorod radio laboratory (NRL) [15].

Fig. 12. O.V. Losev

In the years 1922-1925. In the NRL, the talented self-taught O. V. Losev (1903-1944) experimented with semiconductors. In addition to the ability to detect, he revealed in crystals the disposition to amplify or generate signals. Based on the substance of zincite, he created regenerative receivers of “cristadines” (abbreviated from crystalline local oscillator), RF generators. They worked as successfully as the similarly designed devices on lamps (but less continuously and stably). Later, in individual semiconductors, for example, at the point of contact of a metal needle with a carborundum crystal, he discovered a glow that served as a prototype for future LEDs.

The distinctive works of the young experimental physicist were noticed, including abroad. Later, according to the results of important topics, he who did not have a higher education was awarded the title of candidate of technical sciences (Fig. 12). Until now, no explanation has been given to the phenomenal abilities of semiconductor contact pairs (Losev's “dots,” “glows”) discovered by scientists. It was assumed that by varying the tip of a thin needle over the sensitive zones of the crystal, he was able to find individual micro-areas imitating a transistor [7].

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